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Scientific Reasoning Ability in Adolescence: Theoretical Viewpoints and Educational Implications

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ABSTRACT

Research on the development of ability to control variables during adolescence is reviewed. The first section discusses studies by Piaget and his collaborators, replications of Piagets studies, and related studies by other investigators. Factors which influence performance on controlling variables tasks are delineated; the existance of Piagets stage of formal reasoning is considered. In the second section, attempts to train students to improve in ability to control variables are analyzed. These studies demonstrate that training improves logical thinking under some conditions. It appears that students need to learn to recognize and organize relevant information in addition to learning a particular strategy such as "make other things equal." Suggestions for future research and for development of educational programs are discussed.

Footnote

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Introduction

Ability to control variables or make "other things equal" is of unquestionable importance in many everyday decisions. This was well illustrated in a luxury automobile commercial which argued "When I filled the gas tank of my old economy car and drove to Sacramento and back, I always returned with a quarter of a tank. Now when I fill my new luxury car and drive to Sacramento, I still return with a quarter of a tank." The concept of controlling variables is in fact a difficult one. Many adults have trouble recognizing uncontrolled variables in complex situations like when selecting a car or interpreting information about insurance plans. Scientists are aware of the need to control variables, but often discover that they have overlooked relevant variables. We will refer to ability to separate variables or use the concept of "all other things being equal" as scientific reasoning.

Other writers have summarized earlier work on scientific reasoning (Blasi and Hoeffel, 1974; Lunzer, 1965; Peel, 1971; and Wallace, 1965). While a recent review of adolescent reasoning did not include scientific reasoning (Niemark, 1975), recent research in this area has clarified some important issues for future work.

This review is concerned primarily with scientific reasoning between age 10 and 18. Primary emphasis is placed on studies where the relevant variables are delineated for the subject rather than on studies where the subject is asked to discover variables for himself. Thus, the primary task

in these studies is to separate and control the variables, not determine what the variables are.

The most comprehensive theoretical framework to describe the development of scientific reasoning has been proposed by Inhelder and Piaget (1958). In this paper Piaget's theory will be described, results of both developmental and training studies will be discussed in terms of Piaget's theory, and educational implications in the area of scientific reasoning will be considered.

Piaget's Theory of Formal Operations

The first major research and the most comprehensive work on adolescent reasoning was conducted by Inhelder and Piaget (1958). They administered 15 varied tasks to illustrate the change from what they call concrete to what they call formal operations. The change from concrete to formal operations includes a change from reasoning about real (or observed) events to reasoning about all the possible events in a given situation. At concrete operations, the child reasons only about the specific content of the problem. At formal operations, the child can separate the variables of the problem, and consider the possible values each variable might have. According to Piaget, the formal operational child uses a system of propositional logic (Inhelder and Piaget, 1958, 293-303).

Inhelder and Piaget (1958) postulate that these changes in reasoning ability "depend on three principal factors: maturation of the nervous system, experience acquired in interaction with the physical environment, and the influence of the social milieu". (Inhelder and Piaget, p. 243.) It

should be noted that Piaget does not say these three factors are sufficient to explain development. From infancy, th child's mental development depends on experience with the world of objects and organisms. The social milieu includes the educational experiences of the child. Piaget notes "in general, learning is provoked by situations - provoked by a psychological experimenter or by a teacher, with respect to some diadactic point; or by an internal situation. It (learning) is provoked in general as opposed to spontaneous. In addition, it is a limited process - limited by a single problem or a single structure" (Piaget, 1964, p. 8).

Instruction will not "provoke" the learner unless related to the learner's current level of development. Thus, Piagetian training studies usually involve several pretests to select subjects at the appropriate intellectual level. Additionally, Piaget has emphasized that instruction must encourage the learner to "decenter." The learner decenters by recognizing the invalidity of a particular explanation of a phenomena (or scheme in Piaget's terminology) and actively seeking a new scheme to explain his observation. It appears that "cognitive conflict," as devised by Smedslund (1961), is preferred by Piaget and his collaborators; it is the primary training technique used by Inhelder, Sinclair, and Bovet (1974).

Scientific Reasoning. Inhelder and Piaget (1958) describe the development of scientific reasoning (which they call separation of variables) in conjunction with a number of experiments including bending rods and pendulum. Looking specifically at the transition from concrete to formal thought, we will discuss the results of these experiments.

The procedure for each experiment involves presenting the apparatus, pointing out the variables under consideration and asking the child to find

out what makes one rod bend more than another (bending rods), or what influences the period of a pendulum.

In the bending rods experiment, students are presented with six rods which vary in length, width, shape of crossection (e.g., round or square) and material. They are shown weights which can be hung from the rods and asked to use the weights to find out which rod bends the most. Inhelder and Piaget found that concrete operational subjects can describe the results of their experiments, including the fact that two explanations are possible for the same outcome, but cannot use the "other things equal" scheme. Thus the subject, in describing what Piaget calls a serial ordering, might note "This rod bends more because it has more weight and it's thinner than this rod" but could not set up a fair test to show that thick rods bend more than thin rods. Formal operational subjects attempt to prove something (control variables) rather than describing the reality that they see. Subjects who have just reached the formal level only organize proofs with "all other things equal" in certain cases and even then not for all of the relevant factors. By 14 or 15 subjects, according to Inhelder and Piaget (1958), spontaneously organize proofs using the "all other things equal" scheme.

For pendulum a progression similar to that for bending rods is found. Concrete operational subjects may recognize that the length of the string influences the period but, because they do not control other variables, they conclude that other factors are important as well (when, in fact, they are not). At the beginning of the formal stage, subjects recognize the advantages of controlled experiments, but do not deliberately set them up. In fact, these subjects tend to vary two factors simultaneously and even to

keep the factor under investigation constant. Only at advanced formal operations does the subject set up controlled experiments and discover which variable is important.

In summary, the definitions of concrete and formal thought proposed by Inhelder and Piaget require a reasonable amount of explanation when applied to actual experiments. Clearly the apparatus, number of variables, and type of variable influence whether subjects separate and control variables. The experiments reported by Inhelder and Piaget (1958) do not demonstrate the existance of a general level of functioning since each experiment was tried with different subjects. Additionally, one does not know how the general population would perform since results are reported only for selected subjects.

Replications of Piaget's Work

Researchers using problems devised by Inhelder and Piaget, have confirmed Piaget's main stages in the development of logical thinking but have also found that only a small proportion of adolescents and adults reach Piaget's level of formal operations. It is very difficult to compare the data directly because the studies are not uniform in the age or ability of subjects, the experiments used to measure logical thinking, the experimental procedure, or the standards used to evaluate and categorize responses. The diversity of studies is both a tribute to and a criticism of Piaget's work. Piaget has certainly led others to conduct interesting research. However, because he intended to describe and illustrate the development of cognitive abilities, Piaget's work is imprecise, especially with regard to standardization of categories. In this section we will describe studies establishing

cross-cultural norms for tasks used by Inhelder and Piaget and studies investigating the relevance of the 16 binary operations to logical thinking.

Subjects who reach formal operations. As summarized by others (Blasi and Hoeffel, 1974), many researchers note that small percentages of subjects reach formal operations as defined by Piaget. Dulit (1972) found that only 25-33% of normal adolescents, age 14 to 17, and adults, age 20 to 55, and only 60% of gifted 16 and 17 year olds exhibited formal operations when they tried to solve some of Piaget's experiments. Other researchers who have replicated Piaget's experiments generally report similar rates (Jackson, 1965; Keasey, 1970; Lovell, 1961). These studies, as well as Lunzer's (1965), have also found that subjects who perform a task at one level of thinking may well perform the next task at a more or less sophisticated level, even if the two problems are logically similar.

Looking at the effect of schooling on scientific reasoning, Beard (1962) found that for 8 to 16 year olds the level of logical thinking varied extensively between schools. Almost all subjects in one school failed to either treat the variables in the task independently, or to conclude that only one variable was significant. In another school, nearly all subjects over age 10 were able to separate the variables. Elsewhere, the subjects showed the usual pattern of increasing success with age. Previous classroom experience appeared to play an important part in the ability to control variables.

Mecke and Mecke (1971) are the only investigators who found a sample (of 15 year olds) who all appear to use formal operations. However, they determined that a subject used formal operations if he simply used a systematic approach to eliminate the irrelevant variables in Piaget's pendulum problem. Inhelder and Piaget (1958) consider a systematic approach

to be a necessary, but not sufficient condition for formal operations. A person at formal operations must be able to investigate the variables and then explain how they interact. Thus, Mecke and Mecke's research does not necessarily contradict the other replication studies. It does emphasize the need for clear, workable standards for further research on formal operations. The task used, the subject's previous experience, and the definition of formal operations all affect the proportion of subjects said to exhibit formal operations.

Criticism of Piaget's propositional logic. Several researchers have questioned the usefulness of Piaget's system of propositional logic. Piaget's system is based on 16 logical operations which he says characterize formal thought.

Ennis (1975), in a comprehensive analysis of Piaget's formulation, demonstrated that Piaget's interpretation of material implication is inconsistent with standard propositional logic; he points out that Piaget's system invites overgeneralization and prohibits certain inferences which are accepted in standard propositional logic. Ennis also showed that the ability to "handle propositional logic" in Piaget's terms does not differentiate young children from adolescents: some of the complex operations are used correctly by 7 and 8 year olds, others are used poorly by adolescents. He found no evidence for a quantum jump during the child's development in ability to handle propositional logic. Relevant to our concern with scientific reasoning, Ennis concludes, "There appears to be no connection between isolating variables and possessing the combinatorial system (the 16 logical operations)".

Bynum, Thomas and Weitz (1972) and Weitz, Bynum, Thomas, and Steiger (1973), two of whom are logicians, reexamined Piaget's protocols on one experiment and replicated the same experiment with subjects up to 16 years old. They found evidence for only 8 of the 16 logical operations in Piaget's work and a maximum of 5 in their own protocols. They feel that 6 of the 16 operations occur only in technical works on logic. Osherson (1974) attempted to analyze individual protocols for a series of related logical problems. The 16 operations were ineffective in explaining errors in solving the problems.

Replications studies, then have (1) demonstrated that formal operations is a less unitary trait than implied by Piaget, (2) questioned the role of Piaget's logical operations, (3) shown that only a small portion of adults reach formal operations, and (4) emphasized the need for consistent standards in evaluating formal thought.

Non-Piagetian Studies of Scientific Reasoning

Several researchers have devised their own problems to investigate formal operations. These studies illustrate the many variables that appear to influence the level of scientific reasoning demonstrated by a particular learner. They suggest reinterpretations of Piaget's conception of scientific reasoning.

Level of Formal Operations in the Population

Extending the work of those who replicated Piaget, several studies have assessed the prevalence of formal operations. To determine how many people

regularly use formal operations, Karplus and Karplus (1970) used the Island Problem: "There are four islands: Bird, Snail, Fish, Bean. You can go by plane between Bean and Fish, but you can't go between Bird and Snail... You can also go between Bean and Bird. Can you go (a) between Fish and Bird? (b) between Fish and Snail?" They found that only 40% of the group of physics teachers used formal operations to solve this problem.

Karplus and his coworkers also have devised problems concerning the correct use of ratio and proportional reasoning. They found that only 20% of a large sample of high school students used proportional reasoning consistently in a series of logically similar problems. (Wollman and Karplus, 1974).

Wason and Johnson-Laird (1972) found a very low rate of success among adults who tried to solve the Four Card problem: Four cards, showing respectively a 5, a 2, a B, and a U were presented. Subjects were informed that all cards bear a letter on one side and a number on the other. The question was to decide which of the four cards needed to be turned over to decide whether the statement "Every card with a vowel on one side has an even number on the other" was true. Only 5% of intelligent adults will give the correct solution, the U and the 5. However, Wason and Shapiro (1971) found that performance is improved when thematic material is used and Lunzer, Harrison, and Davey (1972) found that concrete content (full truck, empty truck, red, yellow, and the sentence "Every red truck is full of coal") substituted for the arbitrary letters and numbers of the original problem led to greater success. Thus the evidence for formal operations in the general population is low and the familiarity of the material influences performance.

Variables Relevant to Demonstrating Scientific Reasoning

Role of Experience. Karplus, Karplus, Formisano, and Paulsen (1975) gave both proportional reasoning problems and controlling variables problems to 13 and 15 year olds in seven countries. About 25% of the subjects used formal operations on proportional reasoning while about 20% used formal on controlling variables. The relative difficulty of the two tasks was not consistent from one country to another and the two tasks were not well correlated over the entire population (Karplus, et al, 1975). They concluded that the program used for teaching science and mathematics in each country influenced the likelihood of demonstrating formal reasoning ability. These findings parallel those of Lovell (1961) for schools within England.

Familiarity and number of variables. Linn and Levine (1976) studied three logically similar problems, each involving different variables. They found that not all adolescents (age 11-16) exhibit formal operations when trying to solve logical problems and that success rates vary depending on the familiarity of the variables. The key to their tasks was to change one variable systematically while the other variables were held constant. One of the three, the Seeds Problem, was presented orally as follows:

"Suppose you had two kinds of seeds, white radish seeds and red radish seeds. You want to see which kind will grow tallest in a week. You have two flower pots that are just the same, some soil, water, and fertilizer pellets. What would you do? How much soil would you put in the first pot? The other logically similar problems concerned rolling marbles on a ramp (Ramp Task) and determining which wires were involved in a circuit (Circuit Task). The Ramp and Circuit Tasks were presented with materials while the Seeds Task was presented orally without any materials. Over 90% of the

subjects could solve Seeds, but only about 10% of the same subjects could solve the Circuit, and only 40% of a second group of subjects from the same classrooms could solve the Ramp. Thus the familiarity of the variables influenced success on this task as would be expected.

Several investigators have hypothesized that the number of variables in a given task influences task difficulty. Wozny and Cox (1975) found that the age interacted with the number of variables in a particular task such that two variables tasks (like Balance Beam) were solved by most 12-13 year olds, while tasks with multiple interacting variables (like Floating and Sinking) were seldom solved, even by 16 and 17 year olds. Case (1974) reports similar relationships for younger children between number of variables and the age of the child.

Organization of the problem. Another area that has been investigated is the role of the organization of the problem that the child must solve. Anderson (in Peel, 1971) found that secondary school girls used imaginative responses, the highest type in his study, to a greater degree when they could choose their response in a multiple choice format as opposed to answering an open-ended question. Linn and Levine (1976) found that with a multiple choice format, as opposed to a free format, more 12 to 16 year olds were able to design a properly controlled experiment to solve problems in physics. Wollman (in press) found a similar result with fourth to twelfth graders. He examined the differences between three formats of the same question. In decreasing order of difficulty they were: 1- Devise both conditions of a simple experiment; 2- Complete the second condition of an experiment when the first is provided; 3- Reject an improperly controlled experiment when both conditions are provided. The second format is very

similar to Linn and Levine's or Anderson's multiple choice format. Peel (1971) attributes Anderson's finding to the "educative effect" of the format. Linn and Levine believe that the improved performance is due to the organization of the information.

Amount of available information. A related question is the optimal amount of information provided to the child. Can there be too much information? The results are not completely consistent at this time. When Olson (1966) limited three to nine year olds so that they had to use information one piece at a time, they developed more sophisticated conceptual strategies than when they were allowed free access to all available information.

Using problems involving ratio and proportional reasoning, Karplus and his coworkers report a similar result with children in the fourth to twelfth grades. In their problem (Karplus and Peterson, 1970; Karplus and Karplus, 1972) children were asked to determine the size of a stick figure, Mr. Tall, in large paper clips after they had been shown the size of Mr. Small in small and large paper clips, and the size of Mr. Tall in small paper clips only. When the subjects were able to see both Mr. Tall and Mr. Small, many answers were based on a visual estimate of Mr. Tall. However, when the problem was rearranged so that the children were given the necessary information without actually seeing Mr. Tall, they tried to use the available data in more sophisticated ways. (Karplus, Karplus, and Wollman, 1974).

Linn and Levine (1976) found that performance was impaired for 12 year olds but not for 16 year olds when two different physics problems were organized so that the results were emphasized and the procedure was hidden from view. The young subjects were more likely to make a decision based only on the results that they saw. Many older children would not make a

decision because they realized that they did not have all of the necessary information. Both groups of subjects, however, performed similarly on the problem when the results were not shown. Linn and Levine note that their results are consistent with Piaget's characterization of the transition to formal operations as a change from considering only real events to reasoning about real and all possible events in a given situation.

Peel (1971) reports on two studies that do not directly follow the trend of Karplus, et al, or Linn and Levine. In these studies, children were asked questions after they read passages, some with added information and some without. In one project done by Brydon, there were no significant differences between groups on the frequencies of three levels of responses. In a second study, carried out by Hilton, a slightly greater number of new pieces of information and judgments emerged in the answers when the children read passages with extra information. Peel suggests that this is evidence for a readiness to use information when children reach a certain intellectual maturity.

There are a few important differences between the studies that may explain the varied results. Peel reported on passage reading studies where the additional information was relevant to the problem being discussed. In Karplus' studies and Linn and Levine's, the problems were not reading passages, but involved physical objects that were presented to the children; the additional information provided was not relevant to the problem, it was superflous or even misleading. This is an important area for further research since one important skill in problem solving is the ability to separate the relevant from the irrelevant information.

Extension of Piagetian Theory

Lunzer has examined Piaget's description of the transition from concrete to formal thought, and investigated it using a problem he devised. Lunzer found that what he called "ability to handle multiple interacting systems" more adequately described the transition from concrete to formal than the concepts suggested by Piaget.

Lunzer (1973) and his student, Plockington, have studied the switch problem. In this problem the subject is presented with a box which has one light and 4 buttons to press. The subject was told that one was a switch which would cause the light to come on if it was off and vice versa; one was neutral and would have no effect; one was an on button and this would cause the light to come on if it was off but would have no effect if it was on already; and the last was an off button, the action of this being the exact opposite of the on. To help them keep track of events, subjects were offered 8 labels. These could be used to tag any buttons they identified. The labels were on, off, change, neutral, on or change, on or neutral, off or change, off or neutral. Lunzer found that use of the last 4 labels was nonexistent at age 7, infrequent at age 9, and almost universal at age 11. He hypothesizes that younger children do not use these labels because of an inability to imagine multiple interacting systems. That is, young children cannot accept that they only have sufficient evidence to decide that a button is either off or change, since it must be one or the other.

Summary of Status Studies of Scientific Reasoning

The studies of problems devised by others confirm the results of the replications of Piaget's experiments. The level of formal operations is reached by only a portion of the population of normal and even intelligent

adolescents and adults. The sort of reasoning ability implied by full development of formal thought, that is the ability to apply general principles of problem solving to any problem, does not usually occur. Piaget (1972) has since acknowledged that, unlike the other major stages in cognitive development, it appears that full development of the formal stage is reached by only a segment of normal adolescents and adults; Piaget does believe that all adults develop formal operations in some domain.

Detailed analysis of problems studied by Piaget has revealed a finer structure. Variables which Piaget did not mention have proven important, such as the number of variables and the format of the questions. In seeking a logical structure independent of specific content, Piaget has minimized these factors and emphasized his system of propositional logic (the 16 logical operations). However, it appears that this logical system is difficult to recognize in practice and inadequate for assessing progress in scientific reasoning (Ennis, 1975).

Finally, Piaget has emphasized a change from reliance on concrete experience to use of a formal logical system. Evidence for this sort of change is lacking. Concrete apparatus appears to facilitate performance under some conditions but to present interfering information under others (Linn and Levine, 1976; Karplus and Peterson, 1970). Purely verbal problems appear to be easier than concretely presented problems in some cases but not others (Linn and Levine, 1976; Peel, 1971).

Piaget (1972) has also recently described formal operations as an ideal congnitive competence. In Piagetian terms, it could be that people who are at the level of concrete operations are not naturally exposed to enough experiences of cognitive conflict. They have not had the opportunity to accomodate their cognitive structures to the high level of formal operations.

They may find that concrete operational thought is more than adequate for daily living.

Nevertheless, changes in scientific reasoning ability between age 12 and 16 have been documented (Linn and Levine, 1976; Karplus and Peterson, 1970). A more complete model for these changes is needed. It may be that people who do not use formal operational reasoning for a particular problem have not had the experiences necessary to devise methods to organize the information or to develop the capacities for handling this much information. If the environment does not provide enough opportunities for the experiences that are necessary to go behond concrete thought, can people be deliberately trained to think at a higher level? The next section will deal with this question.

Training in Scientific Reasoning

From the evidence discussed above, it seems that Piaget's stage of formal operations is a level of theoretical or potential competence, not of everyday performance. Additionally, the importance of the number and type of variables in the problem has been demonstrated. Some researchers have attempted to train children so that their performance will approach formal thought; they have had some success in promoting scientific reasoning. Studies will be reported here concerning the promotion of more sophisticated thinking in adolescents. For examples of successful related work with younger children, the reader should refer to Bryant and Trabasso (1971), Bryant (1974), Case (1974), Kohnstamm (1963), and Inhelder, Sinclair, and Bovet (1974).

Research Evidence

Programs which teach scientific reasoning will be discussed by category: (1) Individual Instruction; (2) Programmed Instruction; (3) Classroom Instruction; and (4) Experiential science.

Individual Instruction. One area of investigation has been the use of cognitive conflict as a teaching device. Bredderman (1973) used three tasks based on the bending rods task from Inhelder and Piaget (1958) to train fifth and sixth graders to demonstrate whether the independent variable changed with any particular variable in the problem. They learned to control all the independent variables except the one under consideration, which had to be varied systematically. Bredderman was successful with most, but not all of his subjects. He found little difference between three methods of instruction: 1-reinforcement, where the results reinforce the idea of controlling variables; 2-conflict, where two or three variables were changed simultaneously, resulting in a misleading relation between one independent variable and the dependent variable. The child had to resolve the conflict when the presumed relationship was shown to be erroneous; 3-repetition, where the problem to be solved was presented repeatedly. Bredderman, therefore, found no advantage for cognitive conflict.

Siegler, Liebert, and Liebert (1973) trained 10 and 11 year olds to control variables and draw conclusions from their experiments. Children were trained to recognize that some variables do not influence the outcome of experiments. Siegler, et. al., found that a verbal explanation of the general principles or the use of analogue problems were equally effective in training their subjects to draw the correct conclusions about Piaget's pendulum problem. In an extension of this study, Siegler and Liebert (1975) investigated the effect of conceptual framework and analogue problems on a

combinatorial task. In this case, they found that exposure to conceptual framework plus analogue problems was successful in training both 10 and 13 year olds. The conceptual framework alone was effective for 13 year olds but not 10 year olds. They observed that, for younger subjects, the effect of the analogue problems was to emphasize the need for written records. Older subjects tended to make written records as a result of conceptual framework training along. These two studies appear to suggest that training which helps the child organize the information in a given situation will increase the likelihood of success on the problem. Additionally, 10 year olds need more concrete instruction in how to organize the information than do 13 year olds.

Programmed instruction. Several programmed instruction procedures have been used to promote logical thinking. Gray (reported in Peel, 1971) included both cognitive conflict and strategies for solving problems. Raven (1974) used a short program providing problems and strategies. He found that the program worked best when the criterion questions matched those presented in the program. Although both Gray and Raven reported that their programs enhanced mature thinking, they have not been completely successful in promoting generalization to new problems.

The Productive Thinking Program was designed to train for generalized problem solving skills using self-paced pamphlet materials (Covington, Crutchfield, Davies, and Olton, 1974). In the program, non-school problems such as puzzles and mysteries are presented and the child is taught skills to analyze clues and find a solution. Evaluation of the program reveals that children make substantial gains in thinking skill as measured by a wide range of instruments from essays on poverty to solutions of new

mysteries (Olton and Crutchfield, 1969). The program authors interpret these results as indicating that children can make far more effective use of the capacities they already have when provided with a method for operationalizing their abilities.

Classroom procedures. Peel (1971) reports that one of his students used cognitive conflict as a device to improve the level of thinking. Peel's student, Anderson, developed a program using the teaching method of instruction and class discussion. The topics in judgment were: (1) Recognition of inconsistencies, irrelevances, and partialities. Example: Can you be obedient and clumsy at the same time? (2) Reasoning from propositional statements to arrive at conditions under which statements might be true, false, or inconclusive. (3) Looking for relevant information. (4) Evoking and evaluating explanations. (5) The pitfalls of the implications of the words "all" and "some". (6) A full discussion of judgment problems. An example of a judgment problem is:

> "Statement: In the Middle Ages most men lived all their lives without being able to read. They built beautiful cathedrals, but did not know many of the ordinary, everyday things which every child of twelve knows nowadays. Every age builds upon the knowledge of those who went before. Question: Were the people of the Middle Ages clever or stupid? How do you know?"

Hyram (1957) used induction, going from the specific problem to general principles, to instruct 14 year olds in several concepts of logical thinking. Through guided class discussion, his students arrived at solutions to

a variety of logical problems. After four months of regular discussion periods, the experimental group improved in reasoning ability and logical thinking measured by problems similar to those used for training.

Lawson, Blake, and Nordland (1975) attempted to train 30 high school students to control variables. Students attended 4 training sessions which involved both instruction and experience with apparatus. Students improved in ability to do a problem taught in the program but made no gains in ability to control variables when presented with a new problem. Although the training was very short, students were told how to control variables.

Case and Fry (1973) also trained 15 high school students to control variables. Their program consisted of 12 forty minute training sessions which involved both written materials and apparatus. The major teaching tool was to ask students to think of counter explanations for particular events and then to think of ways to rule them out. Students in the program performed significantly better than controls on a paper and pencil measure of controlling variables and criticizing experiments. Case and Fry used a considerably longer training procedure than Lawson. The pencil and paper test used by Case and Fry was very similar to exercises used in class. It is not known how these subjects would perform on less familiar tasks.

Experiential Science. Another approach to teaching logical thinking has been the development of experiential science programs. Linn and Thier (1975) conducted a large scale study of fifth graders who have studied science using part of the Science Curriculum Improvement Study (SCIS) program, which emphasizes spearating variables. In this program students: 1) try out their ideas using apparatus; 2) are presented with a strategy, and 3) try out the strategy with new apparatus. They found that the logical

thinking ability of the fifth graders who studied the SCIS unit, exceeded controls and approach that of a comparison group of eighth graders.

Linn, Chen, and Thier (1975; in press) report on the development of a Science Enrichment Center designed to improve logical thinking. In this program students choose apparatus and carry out personalized science projects. They found that children who receive an introduction to science concepts and then use the personalized materials make progress in learning to control variables, while in another study, children who did not have an introduction before they interacted with the materials made less progress in controlling variables. Combining the results of Linn, Chen, and Thier (1975) with those of Linn and Thier (1975), it seems clear that once children are alerted to the concept of controlling variables in a setting where the results of the experiments are not emphasized, they can apply these ideas. Having been introduced to the idea of controlling variables, children make progress in applying the idea during free exploration of science experiments. Exploration without the introduction is less effective. A similar observation was made by Duckworth (1974) while evaluating a materials centered science program.

Implications of Training Studies

The great diversity of subjects, mode of instruction, method of measuring learning, and length of training make it difficult to draw precise conclusions about the effect of training. These studies have all provided some combination of strategies and practical experience. It appears that strategies alone help students solve problems similar to those presented in the training program (Raven, 1974; Hyram, 1957; Grey (in Peel), 1971; Olton and Crutchfield, 1969; Lawson, et al, 1975; Case and Fry, 1973) and

help older subjects more than younger subjects (Siegler, Liebert, and Liebert, 1973). Experience with apparatus appears to facilitate ability to solve new problems, especially when combined with strategies (Linn and Thier, 1975; Linn, Chen and Thier, In press; Linn, Chen and Thier, 1975; Siegler and Liebert, 1975). Cognitive conflict or related techniques have been used by many researchers to motivate students (Bredderman, 1973; Case and Fry, 1973; Peel, 1971) but are not universally successful.

These findings suggested that programs which aim to teach scientific reasoning will be most successful if they emphasize recognizing and organizing relevant information rather than if they simply emphasize a particular strategy such as "make all other things equal" to control.

In this section we will discuss (1) relationship of training studies to Piagetian theory, (2) the relationship between cognitive conflict and strategy instruction, and (3) the usefulness of task analysis in training.

Relationship of Training Studies to Piagetian Theory. Collectively, these studies demonstrate that training improves logical thinking under certain conditions. Piaget, commenting on the effectiveness of a classroom demonstration of controlling variables said, "It would be completely useless, the child must discover it for himself." (quoted by Hall, 1970). Piaget emphasizes the importance of direct experience in learning and feels verbal instructions are useless.

It should be remembered that, individually, the studies reported here are limited in scope. In general, the training studies have only fostered logical thinking in one relatively narrow area of problem solving. They have not attempted to demonstrate that the subjects' newly acquired skills have generalized to other related areas. Some writers have asserted that

logical abilities of a formal operational child should be evident in non-scientific fields and even in situations calling for moral judgments (Kohlberg and Gilligan, 1971). Others (Blasi & Hoeffel, 1975) feel that, in the area of personality development, the problems encountered during adolescence lend themselves to using concrete structures rather than formal structures. It is not known whether these training programs have actually disrupted Piaget's sequence of stages, or whether they have only encouraged or accelerated their appearance.

The most successful studies have not totally rejected Piaget's idea about the growth of logical thinking. Instead, they have condensed the process by using the idea of cognitive conflict in a systematic fashion. By presenting selected experiments that forced the subjects to incorporate information that conflicted with their previous ideas, they were led to higher levels of thinking. The goal of the final levels was usually the development of powerful, generalized principles that could be applied to a broad range of problems.

Cognitive Conflict vs. Teaching Strategies. Both cognitive conflict and providing simple strategies for solving problems have been used to describe procedures which enhance scientific reasoning ability. What are the differences in these approaches? Bryant (1974) assumes that problem solvers change their solution strategy when presented with complex as opposed to simple problems. Bryant argues, for instance, that very young children can make transitive inferences and that this ability "exists" in these and older children, but may not be applied to appropriate problems. Thus, the job of the educator is not to teach transitive inference, but to teach strategies for simplifying problems to a level where the appropriateness of transitive inference will be recognized and can be applied.

Piaget, on the other hand, assumes that failure of a transitive reasoning problem reveals that the child does not have a generalized strategy. Followers of Piaget have tried teaching new strategies by inducing conflict. If the learner sees that an approach leads to obviously false conclusions, the learner will seek a new strategy and may select the appropriate one.

Clearly, whether the problem solver has an imprecise strategy or has difficulty simplifying the problem to fit a strategy, the result will be failure of the problem. Strategies can be learned for simple problems. Once the strategy is learned, procedures for simplification of complex problems to fit the strategy can be developed. It might be that generalized strategies for simplifying problems are developed by successful learners.

Usefulness of Task Analysis in Training. Gagne (1970) has pointed out the usefulness of diagramming learning hierarchies for solutions to problems. By attempting to diagram a learning hierarchy based on simplification strategies and conflict, one could set up intermediate steps in the solution process. Using this approach it might be possible to better assess the learning problems of individual children and to determine whether conflict training or strategy learning would be appropriate.

Case (1975) has noted that Gagne's system could be expanded to include analyzing the learning task from the learners point of view. This view is congruent with the suggestion that learning problems of individual children be considered.

Task analysis of problems presented to children has both theoretical and practical significance. Such an analysis should help reveal the relative importance of strategy learning and cognitive conflict in problem

solving. A task analysis should also supply educators with information concerning appropriate methods for instruction.

The task analysis of a controlling variables problem carried out by Linn and Levine (1976) illustrates the value of the approach. Essentially, as discussed above, they found that three questions about the same variables in different formats were differentially related to age. Comparing familiar and unfamiliar variables, Linn and Levine found that the familiarity dimension interacted with the format of the question. Linn and Levine note that Piaget's statements about the change from the "real" to the "possible" are congruent with their results, but do not lead to implications for instruction. They suggest that a strategy for simplifying information in a question would facilitate performance.

Summary and Educational Implications

In reviewing studies of scientific reasoning, we noted that changes do take place during adolescence but that these changes are not as complete as suggested by Piaget's description of formal thought and are influenced by factors not emphasized by Inhelder and Piaget (1958). Researchers interested in clarifying the development of scientific reasoning in adolescence need to be aware of the following factors which appear to influence performance: (1) Number of variables to be considered, (2) Familiarity of the variables to the subject, (3) Previous school experience with variables, (4) Method of presenting information about the task (e.g., results included), (5) Procedure for interacting with the apparatus (e.g., free or constrained), and (6) Subject matter of the problem (e.g., physics vs. biology, consumer affairs or logic).

Research on adolescent scientific reasoning reveals several important findings for instruction:

(1) The most critical information for educators is that only a small number of adolescents can effectively control variables in familiar situations.

(2) Since relatively few adolescents reach formal operations, concrete experience is a valuable aid to learning at all stages of adolescent reasoning. Future researchers need to be concerned with the question of the role of concrete experience in learning. At the moment it appears that concrete experience is necessary but not sufficient. Research such as that of Sigler and Liebert (1975) or Linn, Chen, and Thier (in press), which compare various instructional modes is needed to clarify this question and assist educators in planning programs.

(3) In the current situation where definitive answers do not exist, programs which offer the learner a choice of mode of learning or provide several approaches for teaching the same principles are probably more useful than programs motivated by a particular theory. It may be possible to provide a wide range of choices and assume that the learners will choose experiences reasonably congruent with their abilities.

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